Estimated Responses of Water Quality on the Louisiana Inner Shelf to Nutrient Load Reduction in the Mississippi and Atchafalaya Rivers

Victor J. Bierman, Jr.
Limno-Tech, Inc.
South Bend, Indiana 46637

Abstract

The addition of anthropogenic nutrients from sewage, industrial sources, agriculture and overland runoff has contributed to development of eutrophication in the coastal waters of the northern Gulf of Mexico. The principal source of these nutrients is the Mississippi-Atchafalaya River (MAR) system, the largest single source of freshwater and nutrient inputs to the coastal waters of the United States. An extensive, persistent zone of seasonal hypoxia has been documented in the nearshore bottom waters of the Louisiana-Texas continental shelf.

As part of the NOAA Nutrient Enhanced Coastal Ocean Productivity (NECOP) Program, a mass balance water quality model was applied to the Louisiana Inner Shelf (LIS) portion of the northern Gulf of Mexico. The model was calibrated to field data representing summer average conditions in 1985, 1988 and 1990. As part of the EPA Gulf of Mexico Program, predictive simulations were conducted with the calibrated model to estimate responses of dissolved oxygen and chlorophyll concentrations to potential reductions in nutrient loadings from the MAR system. The objectives of this analysis were to determine whether water quality on the LIS was sensitive to changes in MAR nutrient loadings and to estimate the approximate magnitudes of potential reductions in nutrient loadings that might be necessary to improve present water quality conditions. Results indicated that dissolved oxygen and chlorophyll concentrations on the LIS were responsive to reductions in MAR nitrogen and phosphorus loadings. For a given reduction in MAR nutrient loadings there were large uncertainties in response magnitudes. These uncertainties were due primarily to uncertainties in relationships among MAR nutrient loadings, seaward boundary conditions and sediment oxygen demand, and to inter-annual variability in hydrometeorology.

Background

The addition of anthropogenic nutrients from sewage, industrial sources, agriculture and surface runoff has contributed to development of eutrophication in the coastal waters of the northern Gulf of Mexico. The principal source of these nutrients is the Mississippi–Atchafalaya River (MAR) system, the largest single source of freshwater and nutrient inputs to the coastal waters of the United States. An extensive, persistent zone of seasonal hypoxia has been documented in the nearshore bottom waters of the Louisiana–Texas continental shelf.

As part of the NOAA Nutrient Enhanced

Coastal Ocean Productivity (NECOP) Program, a mass balance water quality model was developed and applied to the Louisiana Inner Shelf (LIS) portion of the northern Gulf of Mexico (Figure 65) (Bierman et al., 1994). The model was calibrated to field data representing summer average conditions in 1985, 1988 and 1990. As part of the EPA Gulf of Mexico Program, predictive simulations were conducted with the calibrated model to estimate responses of dissolved oxygen and chlorophyll concentrations to potential reductions in nutrient loadings from the MAR system (Limno–Tech, Inc., 1995).

Objectives

The objectives of this analysis were to determine whether water quality on the LIS was sensitive to changes in MAR nutrient loadings and to estimate the approximate magnitudes of potential reductions in nutrient loadings that might be necessary to improve present water quality conditions, especially seasonal hypoxia. The purpose of this analysis was not to establish target nutrient loading objectives, but to determine the potential range of nutrient loading reductions that may need to be evaluated in future studies. An important part of this analysis was investigation of uncertainties due to differences in environmental conditions and external boundary conditions.

Modeling Framework

The conceptual framework for the modeling approach is shown in Figure 66. State variables in the model include salinity, phytoplankton carbon, phosphorus, nitrogen, dissolved oxygen and carbonaceous biochemical oxygen demand. The spatial domain of the model is represented by a 21-segment water column grid extending from the Mississippi River Delta west to the Louisiana Texas border, and from the shoreline seaward to the 30–60 meter bathymetric contours (Figure 67). The spatial segmentation grid includes one vertical layer nearshore and two vertical layers offshore. The temporal domain of this model application represents steady-state, summer-average conditions.

Approach to Predictive Simulations

The calibrated water quality model was run for a series of predictive simulations. These simulations involved a range of reductions from 10 to 70 percent on nitrogen and phosphorus loadings from the MAR system. Emphasis was placed on comparison of results to base calibration conditions, not on absolute predictions.

To address uncertainties due to differences in environmental conditions, separate simulations were conducted for July 1985, August 1988 and July 1990 for each load reduction. The most important differences among these three summer average calibration periods were differences in MAR inflows and freshwater advective flow magnitudes and directions on the LIS. To address uncertainties in specification of external boundary conditions, each load reduction simulation was conducted under two separate sets of assumptions: first, all seaward and sediment boundary conditions held constant at base calibration values; and second, all seaward and sediment boundary conditions reduced by the same percentage as the nutrient loading in each simulation.

The rationale for two different assumptions on boundary conditions was twofold: first, these forcing functions are not computed by the model but must be externally specified using available field data; and second, values for these forcing functions are not independent of MAR nutrient loadings, but can be expected to decrease as MAR nutrient loadings decrease. This approach was intended to bracket results of the predictive simulations between present conditions and estimates of future conditions for these forcing functions.

Assumptions

Results of the predictive simulations in this summary are premised on the following principal assumptions:

1. The actual environmental system is fully represented by the conceptual framework of the model.

2. Nitrogen and phosphorus are the only nutrients that potentially limit primary productivity.

3. The actual environmental system is represented at the coarse spatial scale of the model segmentation grid. Near-field gradients in the vicinity of the Mississippi and Atchafalaya River plumes, and near-bottom hypoxia, are not explicitly represented.

4. The actual environmental system is represented in terms of a single "snapshot" in time corresponding to an assumed summer average, steady-state period. The potential influences of meteorological events, shelf-edge upwellings and mesoscale shelf circulation are not explicitly represented.

5. All predictive results represent estimates of future states of the system and do not contain any information on the time frame required for the system to fully respond to imposed changes in nutrient loadings.

6. All predictive results for reduced boundary conditions assume that seaward and sediment boundary conditions will eventually hange by the same percentage as the imposed changes in nutrient loadings.

The results presented in this summary are preliminary results from an ongoing research program and should be considered provisional in nature.

Results of Predictive Simulations

The principal water quality response parameters were bottom water dissolved oxygen concentrations and surface water chlorophyll concentrations. Results are presented in terms of comparisons among different years, different response parameters, and loading reductions for different nutrients. All comparisons are made using the average of dissolved oxygen responses for individual bottom offshore segments (Segments 15–21) and the average of chlorophyll responses for individual surface offshore segments (Segments 8–14).

Predicted responses of average dissolved oxygen and chlorophyll concentrations to nitrogen load reductions are strongly dependent on assumptions for boundary conditions. For example, in response to 70 percent nitrogen loading reductions for 1985 conditions, average dissolved oxygen concentrations increase by less than 10 percent for constant boundary conditions and 35 percent for reduced boundary conditions (Figure 68). For the same predictive simulations, average chlorophyll concentrations decrease by less than 10 percent for constant boundary conditions and 60 percent for reduced boundary conditions (Figure 69).

There are substantial differences in responses of average dissolved oxygen concentrations among different years. For example, in response to 70 percent nitrogen loading reductions, average dissolved oxygen concentrations increase by 150 percent for 1990 conditions and 35–40 percent for 1985 and 1988 conditions under reduced boundary conditions (Figure 70). In contrast to dissolved oxygen responses, there are not large differences in average chlorophyll concentration responses among different years. In response to 70 percent nitrogen loading reductions, average chlorophyll concentrations decrease by 60–70 percent under reduced boundary conditions (Figure 71).

In general, there are not large differences in responses of dissolved oxygen or chlorophyll concentrations between nitrogen and phosphorus loading reductions. There was a tendency, however, for responses to be somewhat greater for nitrogen loading reductions than phosphorus loading reductions, especially for dissolved oxygen responses under reduced boundary conditions.

There was no evidence of significant interactions between nitrogen and phosphorus loading reductions in the predictive simulations. Results of simulations in which nitrogen and phosphorus loadings were reduced simultaneously were generally consistent with results of simulations in which the more limiting of the two nutrients was reduced by itself. That is, if nitrogen was more limiting than phosphorus for a particular load reduction and set of boundary conditions, then results for this simulation were not significantly different when nitrogen and phosphorus loadings were reduced simultaneously by the same percentage.

For 1985 hydrometeorological conditions and reduced boundary conditions, average chlorophyll concentrations are less responsive than average dissolved oxygen concentrations at intermediate (10 to 30 percent) nitrogen loading reductions, and more responsive at higher (50 to 70 percent) nitrogen loading reductions (Figure 72). Differences in responses for 1988 conditions follow patterns very similar to those for 1985 conditions. In contrast to results for 1985 and 1988, average dissolved oxygen responses for 1990 are much greater than average chlorophyll responses for a given nitrogen loading reduction under reduced boundary conditions (Figure 73). These differences occur across the entire range of nitrogen loading reductions from 10 to 70 percent. Differences in maximum responses between these two cases are plus 150 percent (dissolved oxygen) and minus 70 percent (chlorophyll).

Discussion

The responses of dissolved oxygen and chlorophyll concentrations to reductions in nutrient loadings from the MAR system are complex functions of internal model processes and external model forcing functions. Part of this complexity is due to the fact that chlorophyll and dissolved oxygen are non-conservative and are each tightly coupled to other state variables in the model. Another aspect of this complexity is that dissolved oxygen concentration is much more strongly influenced by sediment boundary conditions, primarily sediment oxygen demand, than is chlorophyll concentration. Finally, there is considerable uncertainty in seaward and sediment boundary conditions for both the model calibration periods and the prediction simulations.

The reasons for differences in responses between dissolved oxygen and chlorophyll concentrations are very complex. One reason is that the relative influence of MAR nutrient inputs, seaward boundary conditions and bottom boundary conditions differ between the dissolved oxygen and chlorophyll state variables in the model. Another reason is that dissolved oxygen is coupled to more state variables in the model than chlorophyll. Under reduced boundary conditions, for example, dissolved oxygen responses represent the integrated effects of simultaneous changes not only in dissolved oxygen processes per se, but also of changes in carbonaceous biochemical oxygen demand, phytoplankton carbon (through endogenous respiration) and ammonia nitrogen (through nitrification). Still another factor is that surface chlorophyll and bottom dissolved oxygen concentrations are coupled through the dependence of underwater light attenuation on phytoplankton self-shading. That is, reductions in surface water chlorophyll concentrations can stimulate bottom water primary productivity due to increased light penetration, and hence cause increases in bottom water dissolved oxygen concentrations.

Conclusions

The following principal conclusions were drawn from the data synthesis and modeling simulations conducted in this study:

1. Dissolved oxygen and chlorophyll concentrations on the LIS appear responsive to changes in MAR nitrogen and phosphorus loadings.

2. For a given reduction in MAR nutrient loadings, there are large uncertainties in the magnitudes of dissolved oxygen and chlorophyll concentration responses.

3. Uncertainties in the magnitudes of dissolved oxygen and chlorophyll concentration responses are due to three principal factors:

    a. uncertainty in the relationship between MAR nutrient loadings and seaward boundary conditions

    b. uncertainty in the relationship between MAR nutrient loadings and sediment oxygen demand

    c. inter-annual variability in hydrometeorological conditions on the LIS.

4. Responses of average dissolved oxygen concentrations were more sensitive to differences in sediment oxygen demand than to differences in any other boundary conditions.

5. Responses of average chlorophyll concentrations were more sensitive to differences in seaward boundary conditions than to differences in sediment nutrient boundary conditions.

6. Although differences in results between nitrogen and phosphorus loading reductions were generally not large, there was a tendency for responses to be somewhat greater for nitrogen loading reductions than phosphorus loading reductions, especially for dissolved oxygen under reduced boundary conditions.

7. Estimates of water quality responses to changes in MAR nutrient loadings must be premised on specific assumptions for hydrometeorological conditions on the LIS.

Recommendations

On the basis of the data synthesis and modeling simulations conducted in this study, the following principal recommendations are made:

1. The temporal domain of the present water quality model should be extended to include a time-variable representation of water quality conditions on the LIS during the period of vertical stratification.

2. The vertical scale of the present model segmentation grid should be refined to better

represent near-bottom hypoxia on the LIS.

3. The spatial domain of the present model segmentation grid should be extended so that its seaward boundaries are beyond the influence of freshwater and nutrient inputs from the Mississippi and Atchafalaya Rivers.

4. Advective flows and dispersive mixing coefficients in the model should be determined using the output of a hydrodynamic model.

5. The conceptual framework of the model should be expanded to include dissolved oxygen processes in the sediment and an explicit dissolved oxygen mass balance between water column and sediment segments.

6. The conceptual framework of the model should be expanded to include diatom and non-diatom phytoplankton functional groups, and silicon as a potential limiting nutrient.

References

Bierman, V.J., Jr., S.C. Hinz, D. Zhu, W.J. Wiseman, Jr., N.N. Rabalais and R.E. Turner. 1994. A preliminary mass balance model of primary productivity and dissolved oxygen in the Mississippi River Plume / Inner Gulf Shelf region. Estuaries. 17(4):886–899.

Limno-Tech, Inc. 1995. Estimated Responses of Water Quality on the Louisiana Inner Shelf to Nutrient Load Reductions in the Mississippi and Atchafalaya Rivers. Report prepared for Louisiana State University and A&M College, Baton Rouge, Louisiana, and submitted to U.S. Environmental Protection Agency, Gulf of Mexico Program Office, Stennis Space Center, Mississippi.

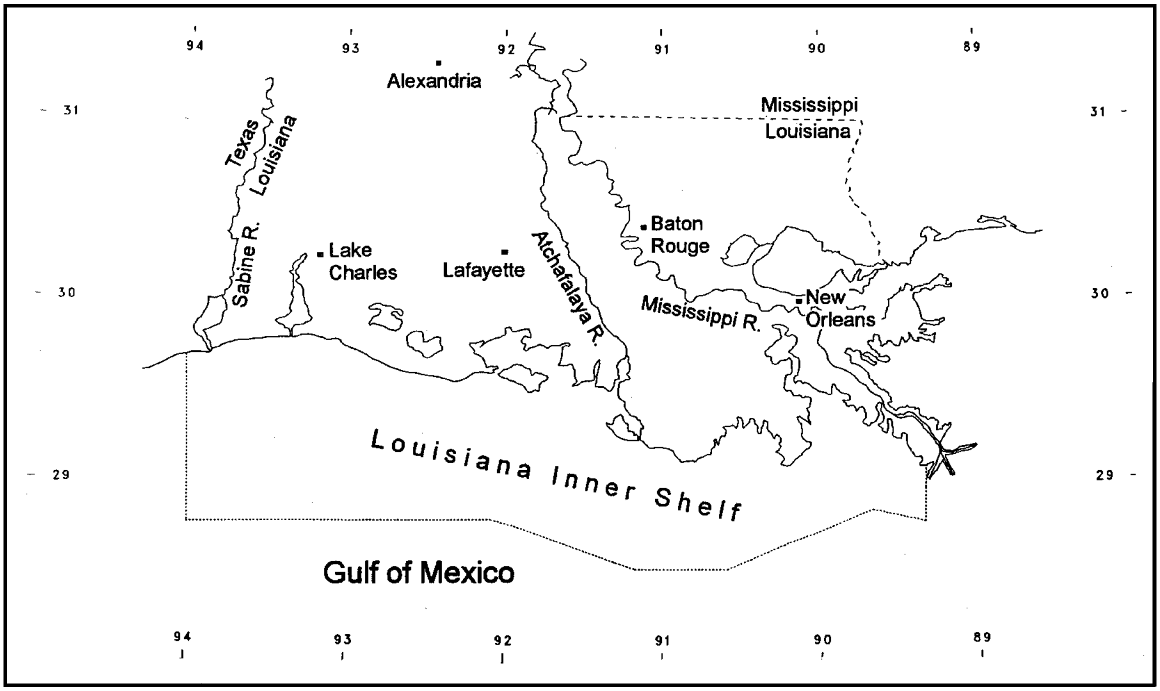


Figure 65.
Location map of study area.

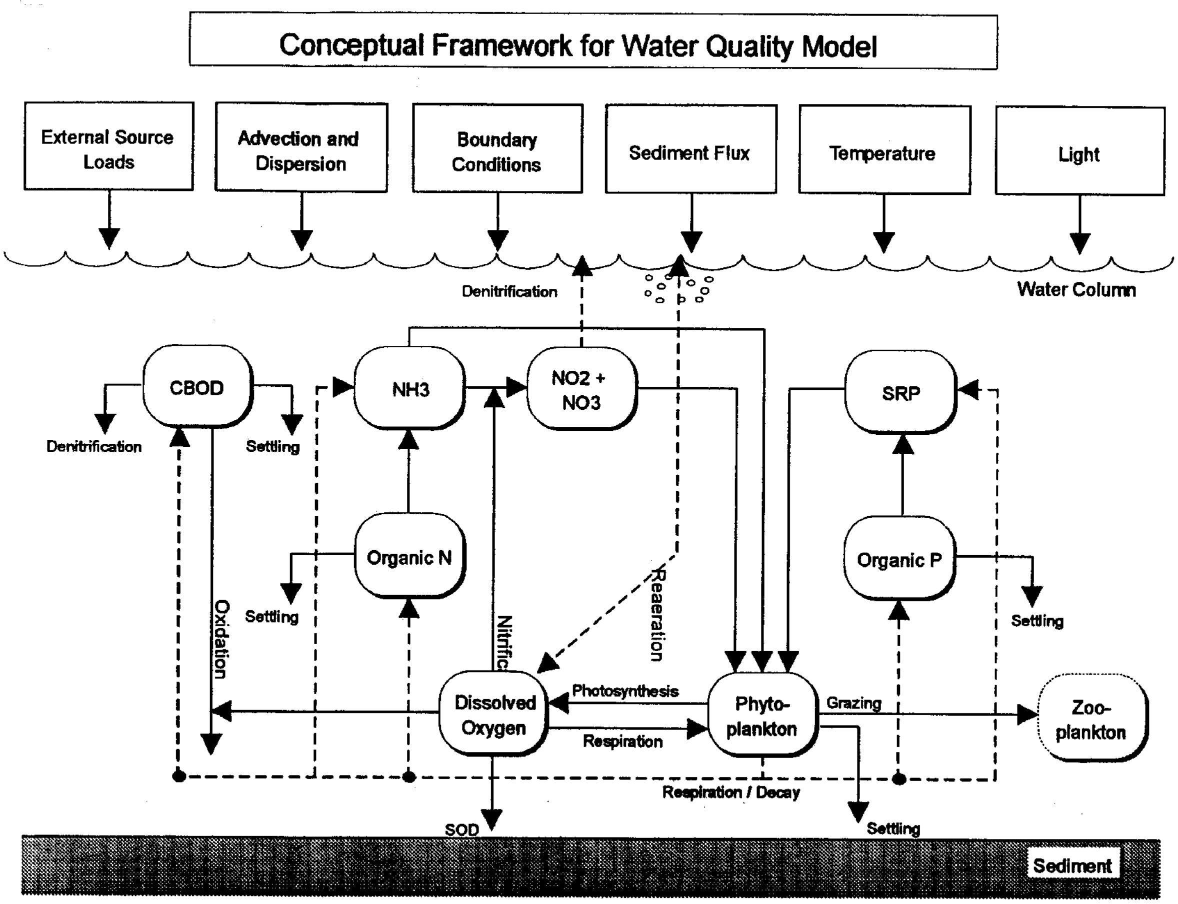
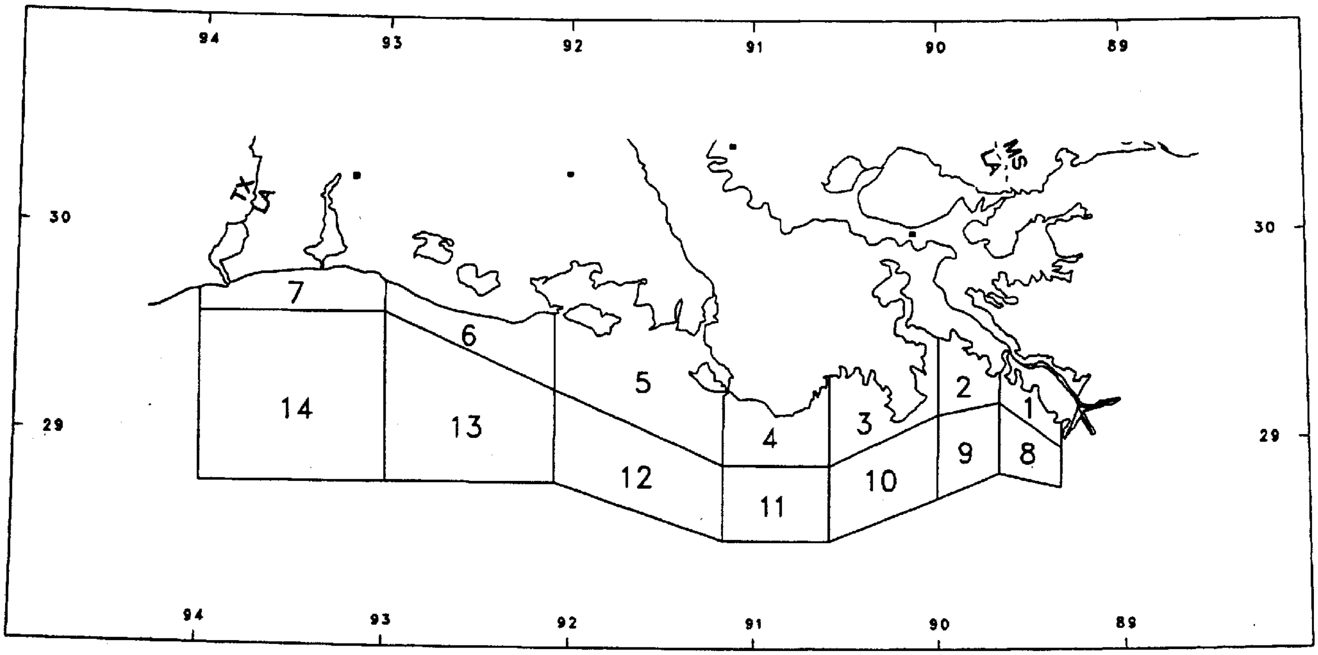


Figure 66.
Schematic diagram of principal model state variables and processes.



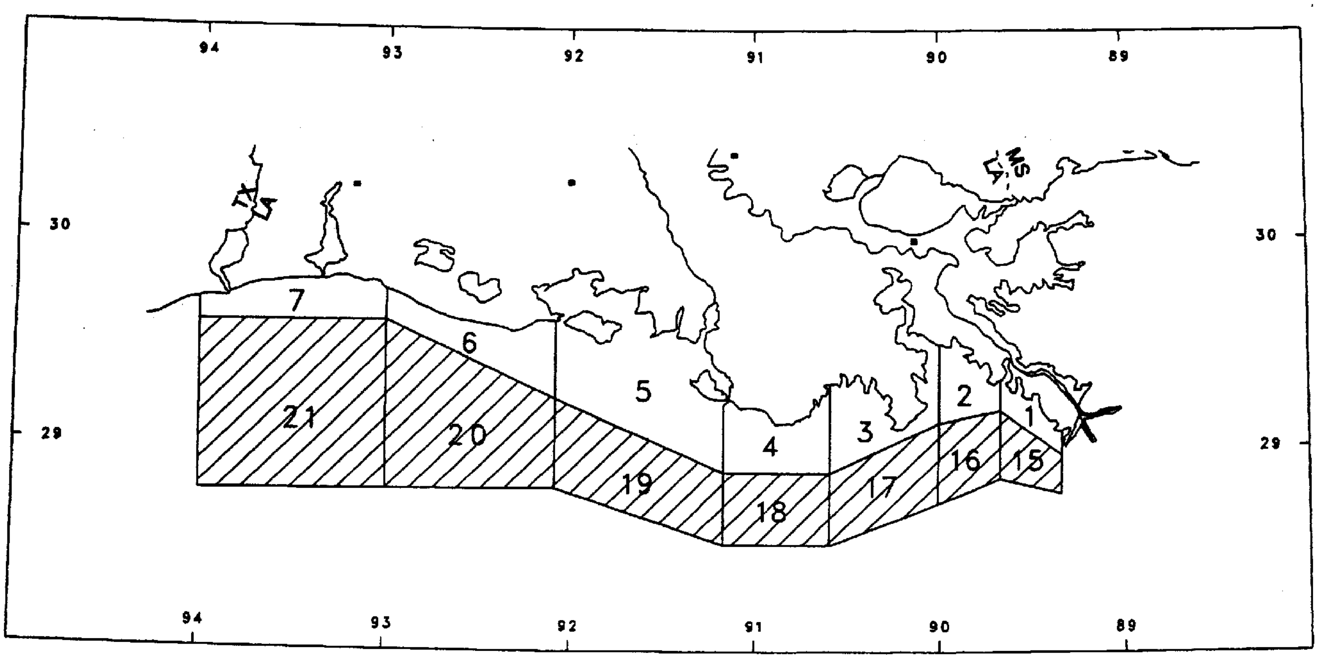


Figure 67.
Model spatial segmentation grid for the Louisiana Inner Shelf.

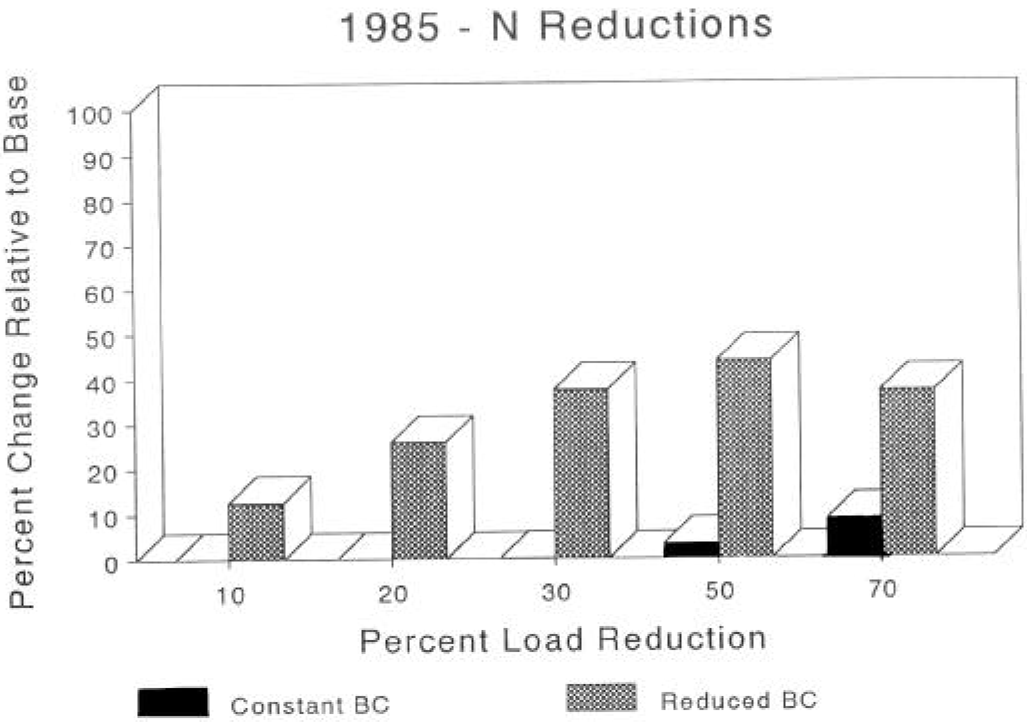


Figure 68.
Predicted responses of average dissolved oxygen concentrations to nitrogen loading reductions for 1985 conditions under constant and reduced boundary conditions.

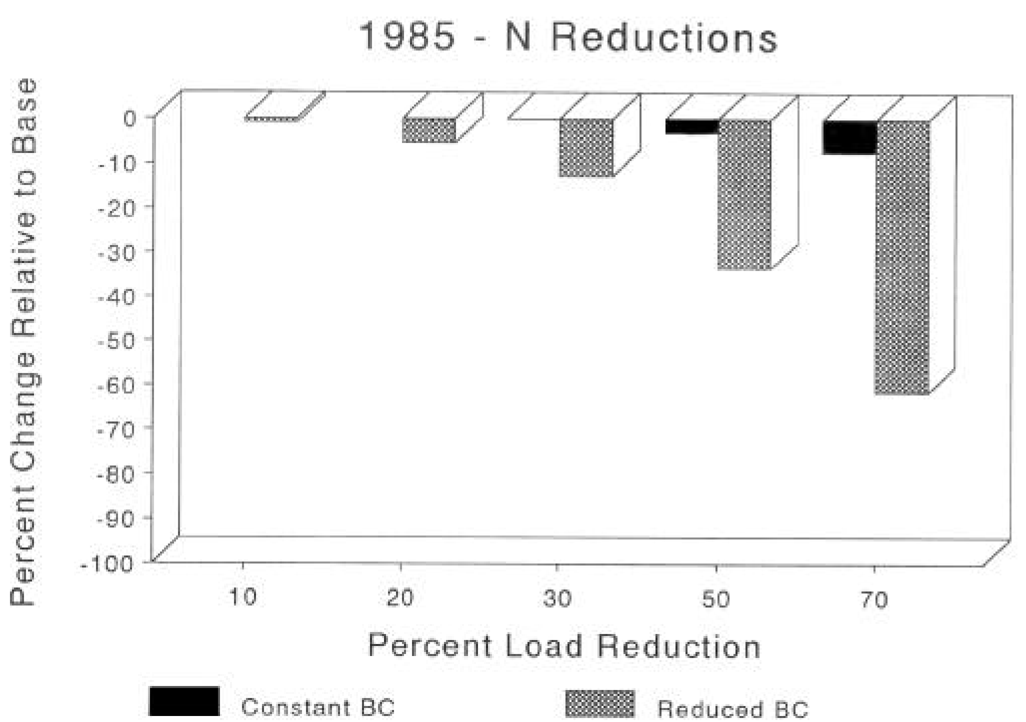


Figure 69.
Predicted responses of average chlorophyll concentrations to nitrogen loading reductions for 1985 conditions under constant and reduced boundary conditions.

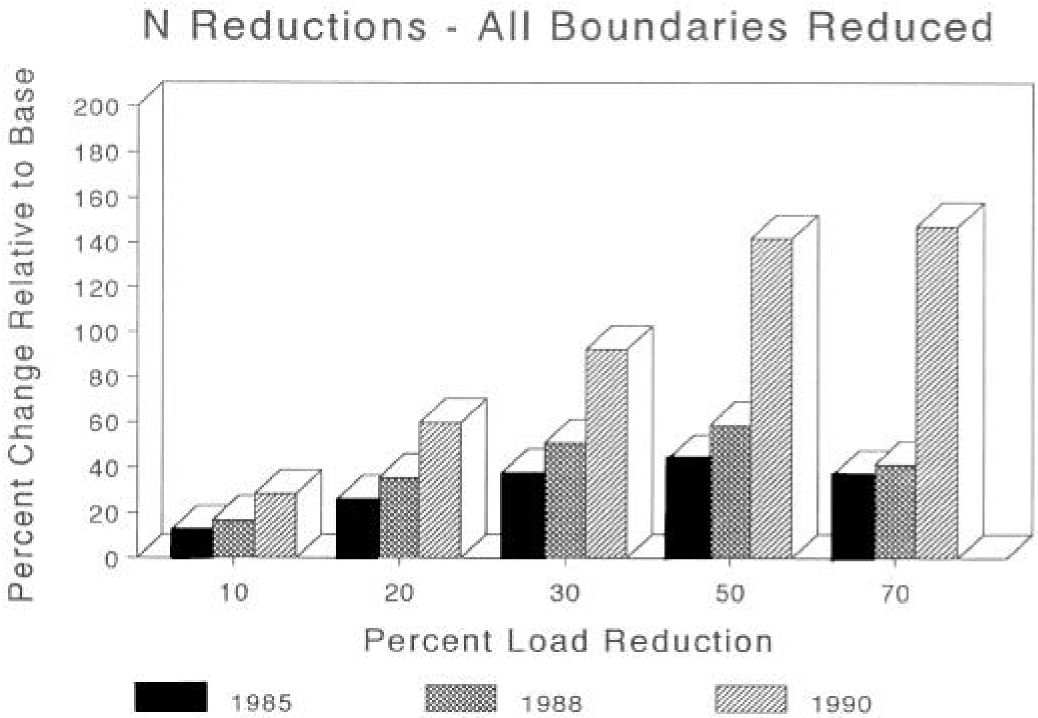


Figure 70.

Predicted responses of average dissolved oxygen concentrations to nitrogen loading reductions for 1985, 1988 and 1990 conditions.

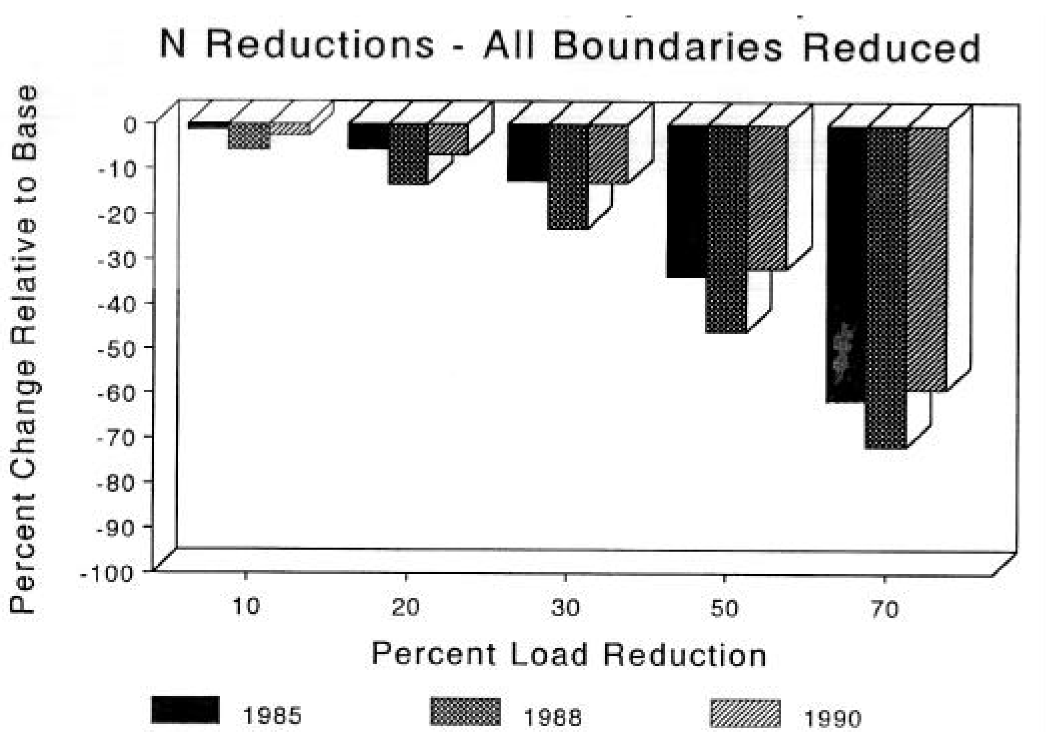


Figure 71.

Predicted responses of average chlorophyll concentrations to nitrogen loading reductions for 1985, 1988 and 1990 conditions.

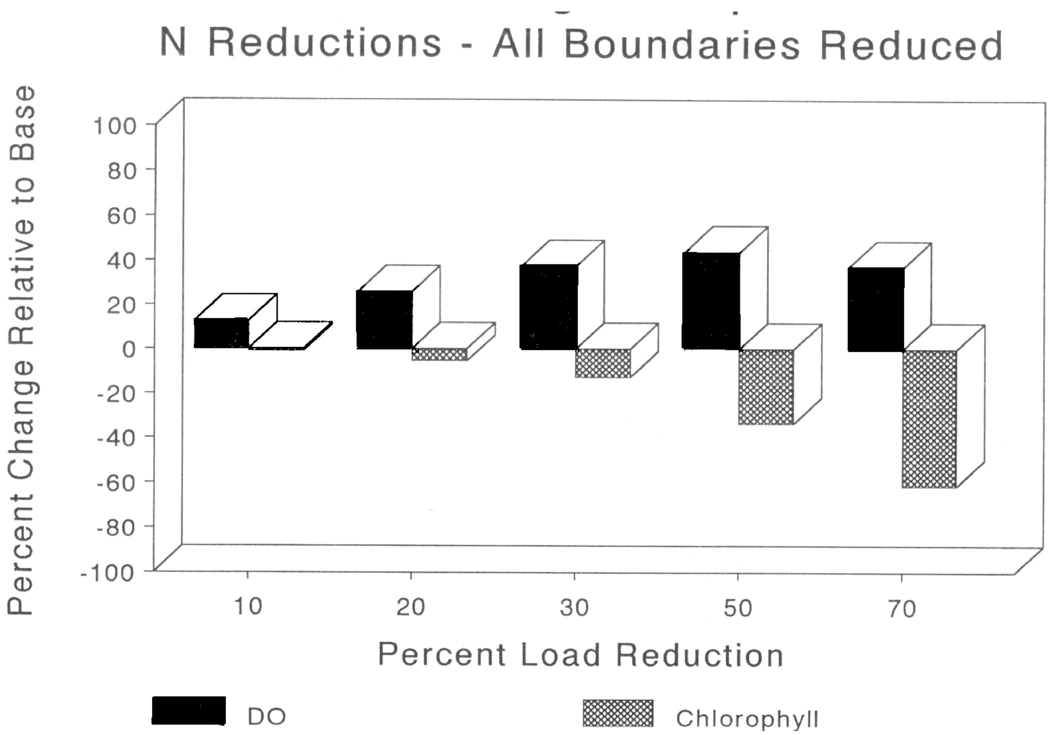


Figure 72.
Predicted responses of average dissolved oxygen and chlorophyll concentrations to nitrogen loading reductions for 1985 conditions.

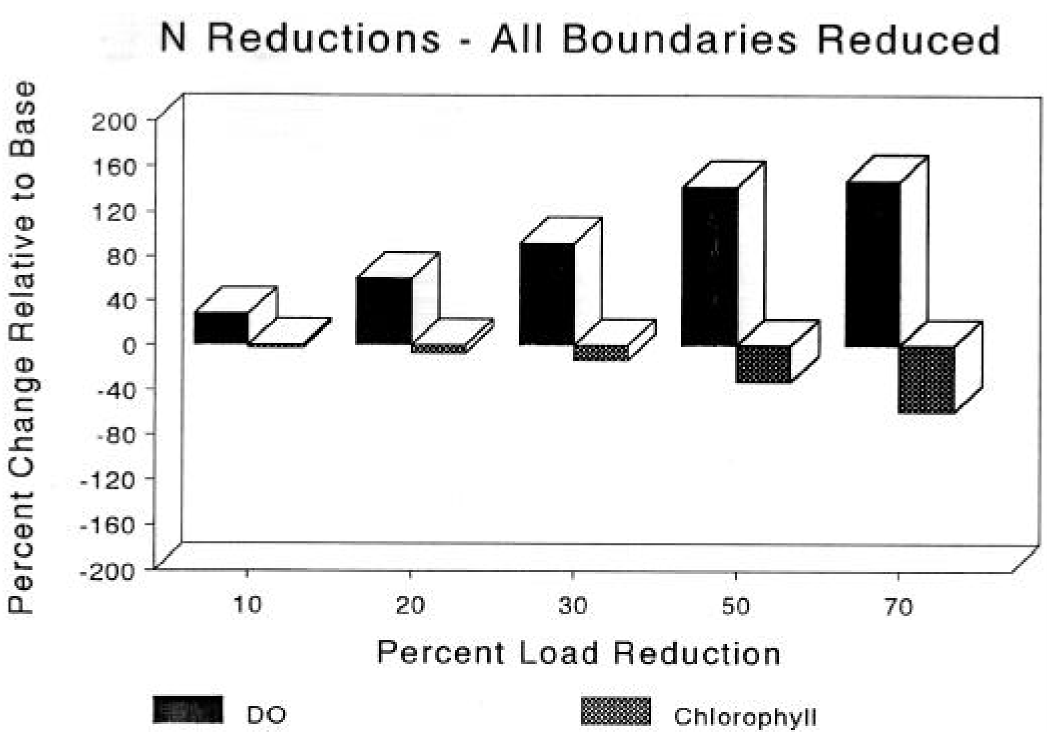


Figure 73.
Predicted responses of average dissolved oxygen and chlorophyll concentrations to nitrogen loading reductions for 1990 conditions.

Presentation Discussion

Vic Bierman (Limno-Tech, Inc.—South Bend, IN)

Mr. Bierman left conference due to an emergency.